Appendix E

Hydrogen Tutorial

Hydrogen is the simplest and lightest element. Although hydrogen is all around us and accounts for 75 percent of the entire universe's mass,[i] on Earth it is found only in combination with other elements. For example, hydrogen readily bonds with oxygen to make water, and with carbon to make organic matter. Before it can be used as a fuel, hydrogen must be separated from these other elements. The process to “produce” hydrogen requires energy, just as it takes energy to make other transportation fuels like gasoline and to compress natural gas. For example, hydrogen can be produced from molecules called hydrocarbons by applying heat. This “reforming” process is currently used to make hydrogen from natural gas and is the cheapest method of hydrogen production. An electrical current can also be used to separate water into its components of oxygen and hydrogen in a process called electrolysis. In addition, certain types of algae and bacteria use sunlight as their energy source and give off hydrogen under certain conditions.[ii] Hydrogen gas exists in the form of two tightly bound hydrogen atoms (H_2).

Today, hydrogen is primarily used for industrial processes such as ammonia manufacturing and petroleum refining. It has also been widely used in NASA's space program as fuel for the space shuttles, and in fuel cells that provide heat, electricity and drinking water for astronauts.

Fuel cells are devices that produce electricity in an electrochemical reaction between hydrogen and oxygen. Because of the strong promise fuel cells hold as commercially viable, clean and efficient electrochemical power sources, all of the world’s major automobile manufacturers are developing hydrogen fuel cell vehicles. Other applications of fuel cell systems are in stationary applications to generate environmentally friendly electricity and usable heat. In both of these fuel cell applications, California is likely to be the earliest American market for commercialization.

Fuel cell vehicles are in fact electric vehicles (EVs). Like battery-powered EVs, they use efficient electric-drive systems. However, instead of electrons being stored in batteries, they are generated in the fuel cell through the reaction between hydrogen and oxygen. Fuel cells can be thought of as batteries that never lose their charge -- hydrogen can be continuously supplied from an external fuel tank, and oxygen can be extracted from ambient air. This provides fuel cell vehicles with many desirable attributes, including zero emissions, fuel economy that is twice as high as most ICEs, a driving range required by consumers and refueling times comparable to gasoline vehicles.

Figure 1.a illustrates the basic operation of a hydrogen fuel cell vehicle powered by a proton exchange membrane (PEM) fuel cell, which is the type being

developed for automotive applications. Figure 1.b shows how a PEM fuel cell converts hydrogen into electricity. While today's prototype fuel cell automobiles appear similar to conventional vehicles on the outside, the drive train components and their layout can be quite different. The challenge most cited by experts as a potential shortcoming of hydrogen vehicles for consumers is the storage of enough fuel so that a hydrogen vehicle's range is similar to that of a traditional internal combustion engine vehicle.

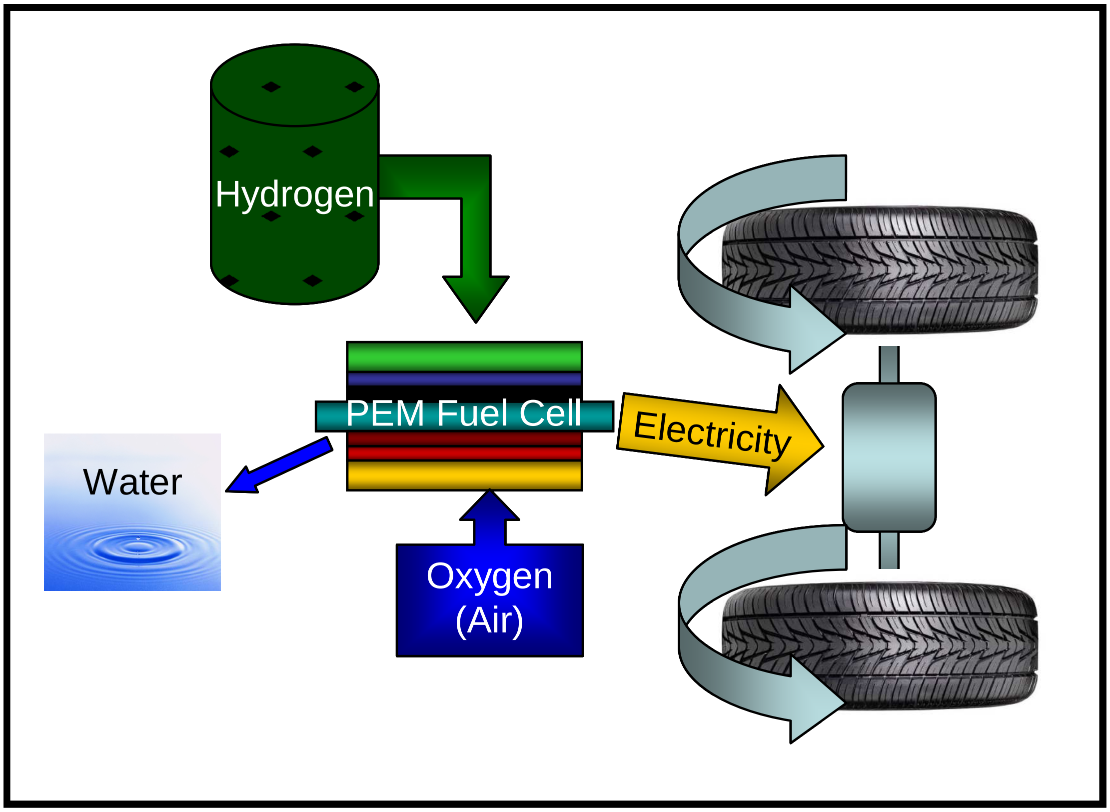
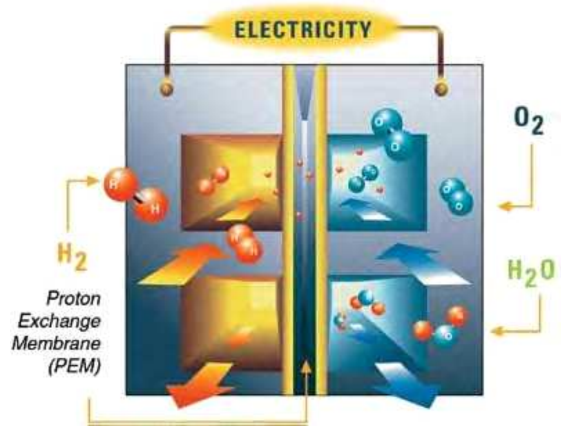


Figure 1.a Basic Operation of a Hydrogen Fuel Cell for Automobiles.

Proton exchange membrane (PEM) fuel cells are the type most commonly used for automotive applications.



Graphic courtesy California Fuel Cell Partnership

When hydrogen enters a PEM fuel cell, its electrons and protons are separated. A membrane in the cell selectively allows the protons to pass through, while the electrons are routed to provide the electricity to power the motor that propels the vehicle. On the other side of the membrane, the hydrogen combines with oxygen from the air to form water and heat.

Figure 1.b Basic operation of a PEM fuel cell

Hydrogen can also be used to power vehicles with internal combustion engines (ICEs), much as natural gas is currently used. At least two major automobile companies are working to develop and commercialize hydrogen ICE vehicles. Hydrogen ICE vehicles face the same hydrogen storage issues as fuel cell vehicles. Presently the cost of a hydrogen ICE vehicle is less than 25% of a hydrogen fuel cell vehicle. Compared to gasoline ICEs, hydrogen ICEs offer better mileage, do not consume fossil fuels and have extremely low emissions[iii] (equivalent to the California Air Resources Board's SULEV rating).

Why Hydrogen?

Commercialization of vehicles and technologies that use hydrogen as fuel can provide benefits to California. Benefits include a more diverse and secure transportation energy supply, an improved environment, and the opportunity for economic growth.

Energy Diversity and Security Benefits

Hydrogen is an Integral Part of California's Long-Term Energy Strategy

California's transportation sector is nearly 100% dependent on gasoline and conventional diesel, both of which are non-renewable and in finite supply. Demand for these fuels in California alone has grown nearly 50 percent in just the last 20 years and will continue to grow. At the beginning of this decade, California had a population of 33.8 million people, driving 24 million registered vehicles, and consuming more than 17 billion gallons per year of gasoline and diesel fuel. By 2020, it is projected that 45.5 million Californians will operate 31.5 million vehicles consuming about 24 billion gallons of gasoline and diesel fuel.[iv]

California's petroleum refining capacity has not kept pace with this demand. In fact, since the mid-1990s, in-state refining capacity has decreased nearly 20 percent, and California has shifted from being a net exporter of petroleum to a net importer.[v] During this period, a combination of refinery outages, marine and distribution constraints and other factors has led to volatile gasoline and diesel prices.

Several options are available to reduce the demand for petroleum transportation fuels. Conservation through the production of more fuel efficient motor vehicles is an effective means of reducing demand for petroleum. Encouraging greater use of available, non-petroleum fuels, such as natural gas and synthetic diesel fuel, can also reduce petroleum demand. Together, these near-term approaches can reduce demand for petroleum fuels to current levels or below over the next two decades. Beyond the near-term, greater use of non-petroleum fuels will be necessary to meet the ever growing demand for clean transportation fuel. A detailed assessment by the California Energy Commission and the Air Resources Board showed that, from an environmental and economic standpoint, hydrogen fuel cell vehicles provide an attractive long-term approach for continuing to reduce California's petroleum dependence.[vi]

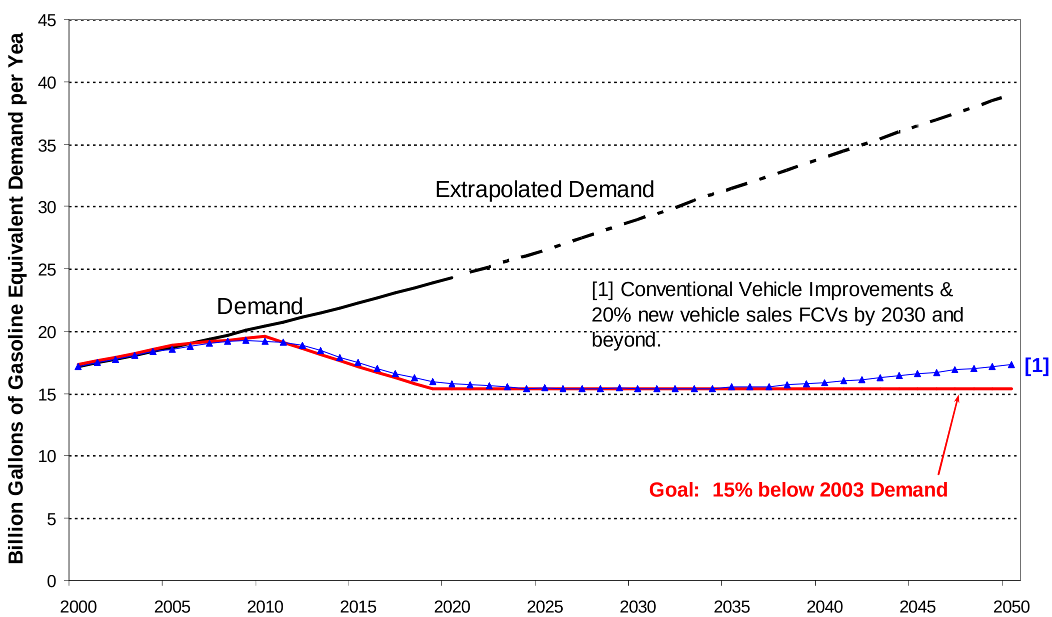


Figure 2: Growth in Demand for On-road Petroleum Fuels*[vii]*

Hydrogen Can Diversify and Stabilize California's Energy Supply

Hydrogen can diversify and stabilize California's energy sector and stabilize the energy supply. Hydrogen occupies a unique niche at the confluence of transportation, electricity, and heating energy. For example, hydrogen "energy stations" are electricity production units that can also provide heating, cooling and power for homes and businesses, while producing enough additional hydrogen that can be used to fuel vehicles. Hydrogen can be used to store, move and deliver energy in a usable form to consumers. In this manner, hydrogen can be used to store renewable energy that is intermittent in nature for times periods when the demand exceeds the electricity supplied by the renewable resource. The properties of being an energy carrier can improve and stabilize the way our existing electricity system meets growing consumer demand. Hydrogen is able to displace petroleum use in our transportation sector while also helping our over-extended electricity production and transmission system, thereby offering the promise to diversify and stabilize California's overall energy portfolio.

Hydrogen Can Be Produced From Renewable Resources

An energy infrastructure based on hydrogen and renewable resources is inherently sustainable in nature. The term "renewable resources" (or simply "renewables") refers to resources such as wind, solar, geothermal, and waste resources such as biomass. All of these types of renewable resources are available in California and can be used to produce hydrogen. Hydrogen produced from renewable resources results in near-zero emissions of all pollutants, and reduces reliance on limited resources such as oil and natural gas. Further, to the extent California takes the lead in developing technology to produce hydrogen from renewable resources, our state is in an attractive long-term economic position as demand for such technology is expected to grow significantly worldwide.

Some stakeholders argue that renewable resources would be better utilized, from the perspective of public health and environmental protection, to produce electricity rather than hydrogen. The amount of energy required to meet the goal of 20% hydrogen production from renewables is very small. Even if the renewable resources dedicated to producing hydrogen were shifted to the electricity sector, the impact would be less than 0.1 percent of the total sector. The EO Team believes it is necessary for the state to support the use of renewable resources in order to establish relationships and develop supply chains between renewable energy producers and hydrogen producers.

Hydrogen Production

Hydrogen has been safely used as an industrial gas in manufacturing, fertilizers, and food processing for nearly 50 years. Using hydrogen as a vehicle fuel, however, is unfamiliar to most Californians. In the spring of 2005, California became the first state to classify hydrogen as a transportation fuel. Fundamental to articulating why hydrogen is an important solution to air quality, climate change and energy diversity challenges is understanding where it comes from or how it is made. The following discussion summarizes some of the most common production methods and the environmental impacts associated with these pathways.

The most common ways to produce hydrogen are electrolysis, which uses electricity to split water into hydrogen and oxygen, and reformation, which uses steam to separate hydrogen from methane (or natural gas). Less common is gasification, a process that uses steam and oxygen at high temperatures to convert coal, petroleum coke or biomass to a hydrogen-rich gas. There are advantages and disadvantages to each technology.

Electrolysis: The Blueprint Plan recognizes that using fossil fuel derived grid electricity to produce hydrogen via electrolysis can produce more emissions from a source to wheel perspective, relative to gasoline. However, if electricity is generated from zero carbon sources such as hydro, nuclear, geothermal, solar, or wind, the source to wheel emissions are significantly lower than gasoline.

Reformation: Steam methane reformation using natural gas as a fuel source is currently one of the most economical way to make hydrogen. This process produces significantly fewer emissions from a source to wheel perspective relative to gasoline. However, the Blueprint Plan recognizes that using natural gas, a fossil fuel, is not a sustainable solution to energy dependence. Reformation can however, be used to produce hydrogen from renewable sources of methane, ethanol, methanol, biogas, and landfill gas. The Blueprint Plan analysis found that production of hydrogen via biogas reformation produces fewer emissions than natural gas reformation. Source to wheel analyses are still required to determine relative emissions associated with reformation of ethanol and methanol.

Gasification: Production of hydrogen via gasification is less common. Gasification can be applied to convert petroleum coke, coal, waste biomass resources and other waste resources into hydrogen or electricity. While, the Blueprint Plan found that emissions from the gasification of petroleum coke were no better than gasoline, gasification of waste biomass could result in overall reduced emissions of criteria pollutant and greenhouse gas emissions. This notion is based on the fact that biomass resources, when left alone to decompose in landfills or the natural environment, will emit greenhouse gases such as carbon dioxide and methane.

Environmental Benefits

To make a fair comparison of the full environmental impacts of various motor vehicle types requires characterization of as many of these "Well to wheel" or fuel cycle emissions as possible. Fuel cycle emissions are illustrated in Figure 3 below.

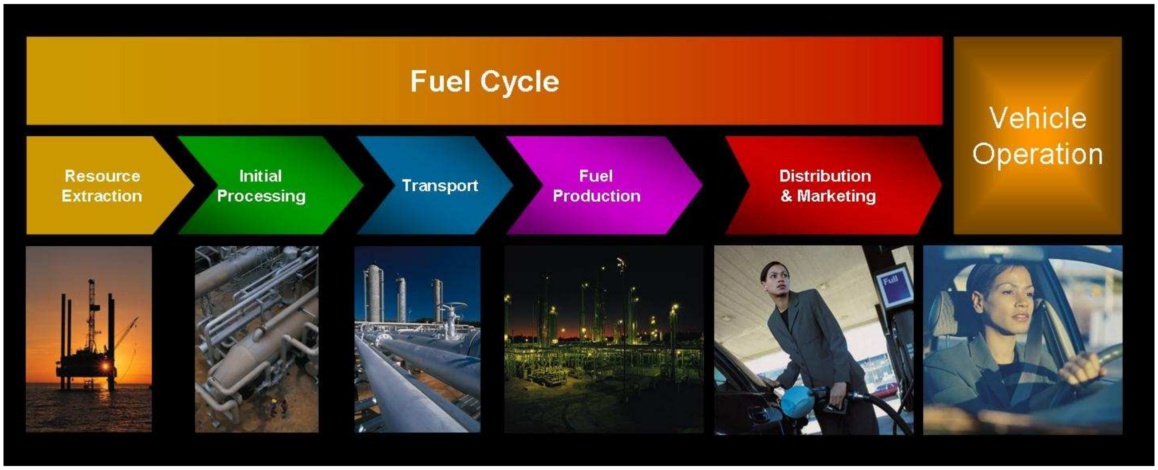


Figure 3. Fuel Cycle Emissions Illustration[viii]

The well to wheel analysis includes all of the steps in the fuel cycle. Those steps include production of the fuel, transport of the fuel to the point of use, pumping the fuel into the vehicle and vehicle operation. Based on this type of analysis, the environment benefits of using hydrogen to power motor vehicles or generate electricity fall into two major categories 1) reduction of smog forming and toxic emissions, and 2) reduction of greenhouse gas emissions.

Hydrogen Can Reduce Smog-forming and Toxic Emissions

The use of hydrogen as a transportation fuel can result in lower emissions of criteria pollutants when compared to those of petroleum products. These smog-forming and toxic emissions benefits are dependent on the systems and materials used to produce and consume hydrogen. If hydrogen is produced using electrolysis and the electricity is derived from renewable resources then the well to wheel emissions are zero—the entire fuel cycle is sustainable. Relative to gasoline refining, particulate emissions can be higher if hydrogen is generated by electrolysis dependent on electricity derived from coal.

Distribution emissions in the hydrogen fuel cycle are only important if the hydrogen is produced in a central plant and has to be distributed by gasoline and diesel trucks. Distribution emissions are zero if the hydrogen is produced where it is used (called distributed generation) or if the hydrogen is transported from a central location by a zero emission vehicle.

Fueling emissions are never a factor in the hydrogen fuel cycle because any hydrogen that escapes during vehicle fueling are non-toxic, unlike those of petroleum based fuels.

Tailpipe emissions are zero if hydrogen is used in a fuel cell vehicle. The only emission is water. The emissions consist only of only near-zero amounts of oxides of nitrogen in a hydrogen combustion engine.

In contrast, California's 24 million gasoline- and diesel-fueled vehicles directly or indirectly cause a variety of serious pollution problems in our state. Adverse environmental impacts occur during virtually every step associated with using these vehicles: from the beginning of the fuel production phase to the tailpipe. The refining of petroleum into gasoline and diesel fuel results in emissions of reactive organic compounds, including toxic compounds, oxides of nitrogen and particulate. Refineries are typically one of the largest stationary sources of emissions in the state. The distribution of gasoline from the refinery to the retail service station results in fuel evaporation emissions at every point of transfer, including transfer to the car. Burning petroleum fuels in vehicles results in emissions of volatile organic compounds, some of which are toxic, oxides of nitrogen, carbon monoxide, and particulate.

For the entire fuel cycle, hydrogen vehicle emissions of oxides of nitrogen, volatile organic compounds and carbon monoxide are clearly less than gasoline or diesel, while the relative comparison for particulates depends on how the hydrogen is made.

This discussion points to the importance of producing hydrogen in the most environmentally sound manner. Zero emitting options are available such as solar/electrolysis, which can result in zero emissions for the entire fuel cycle.

Hydrogen Can Reduce Greenhouse Gas Emissions

As with smog-forming emissions, the fuel cycle greenhouse gas (GHG) emissions of hydrogen vehicles depend on the method of hydrogen production. In this case emissions also depend on what type of vehicle uses the hydrogen, because fuel cell vehicles are more efficient than combustion vehicles that burn hydrogen. And both hydrogen fuel cell and ICE vehicles are more efficient than conventional gasoline vehicles.

Shown in Figure 4 are the results of an analysis of the fuel cycle greenhouse gas emissions of hydrogen compared to gasoline, for both fuel cell and hydrogen internal combustion engine (ICE) vehicles. Notable is that production of hydrogen from renewable-based electricity results in near zero emissions. Reforming of natural gas also results in lower fuel cycle greenhouse gas emissions. However, production of hydrogen using grid electrolysis results in greater greenhouse gas emissions than gasoline. Again this points out the importance of developing the CA H2 Net using the lowest emitting technologies for producing hydrogen.

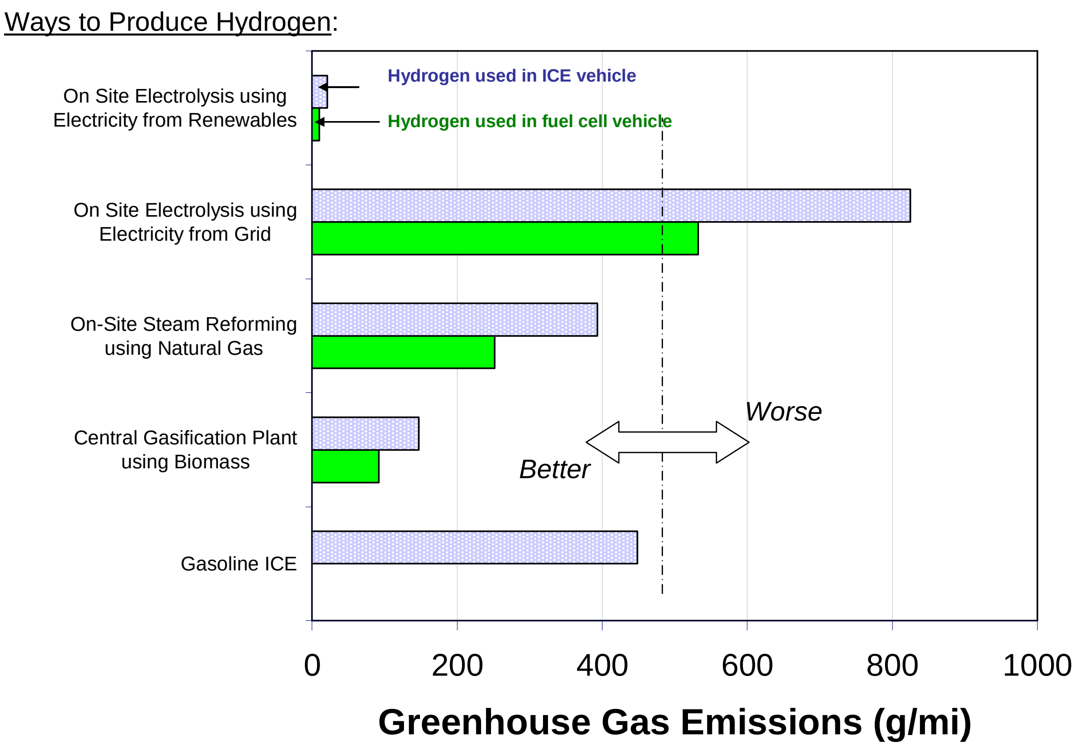


Figure 4. Full Fuel Cycle GHG Emissions (Well to Wheel)[ix]

Economic Development Benefits

California has a long history of being at the forefront of emerging high-technology industries. State officials have recognized that these industries can create jobs as technologies develop and flourish in the world marketplace. More than 100 companies are working on prototype hydrogen-related technologies in California; examples include hydrogen production systems, fuel cells, hydrogen storage systems, and safety-related devices. Many companies have initiated similar efforts in other states. If California continues to lead in creating demand for hydrogen fueling stations and products, companies with related technologies are more likely to choose our state to locate new technology centers and manufacturing facilities. Expansion of hydrogen-related research, development and demonstration efforts will help generate new jobs, businesses, and industries in California.

Educational Benefits

Just as California is home to the world's leading businesses and industries, so to is it home to some of the world's finest universities. The University of California (UC) and California State University (CalState) systems have well-established programs related to the development of the hydrogen economy and its attendant technologies. California's universities have been at the forefront in engineering vehicle systems; fuels development, production, and distribution; emissions testing; traffic modeling and infrastructure development; and more. They are also among a cadre of early-adopters and testers of hydrogen technologies and will be essential components to the early-phase rollout of the CA H2 Net. Integrating the UC and CalState systems into the development of the CA H2 Net will help sustain their vital role in the developing hydrogen economy, as well as serve to attract the world's best researchers and educators in the field.

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[i] California Energy Commission, *Energy Story: Chapter 20*; online at http://www.energyquest.ca.gov/story/chapter20.html.
[ii] Ibid.
[iii] Equivalent to the Air Resources Board's Low Emission Vehicle rating of SULEV
[iv] California Energy Commission, California Air Resources Board; *Reducing California's Petroleum Dependence, Joint Agency Report*; August 2003; Publication Number P600-03-005f.
[v] "Reducing California's Petroleum Dependence Report," CEC/ARB joint agency report, August 2003.
[vi] California Energy Commission, California Air Resources Board; *Reducing California's Petroleum Dependence, Joint Agency Report*; August 2003; Publication Number P600-03-005f.
[vii] Ibid.
[viii] Images illustrate fuel cycle for petroleum fuel production.
[ix] Hydrogen production methods depicted in this Figure represent the high and low ends of emissions impacts. This Figure is representative of light-duty vehicles only.